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First ^{40}Ar-^{39}Ar Ages from Low-T Mafic Blueschist Blocks in a Franciscan Mélange near San Simeon: Implications for Initiation of Subduction

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ABSTRACT

The Franciscan Complex of California is a type example of an accretionary prism with widespread high-P/T subduction-zone metamorphism. Low-T, fine-grained, lawsonite-bearing mafic blueschists encased in a shale-matrix mélange near San Simeon have been dated for the first time. ^{40}Ar-^{39}Ar ages were obtained for phengite separated from four blocks and from an actinolitic rind on the margin of one of the blocks. The three blocks with lawsonite + epidote yield ages of between 154 and 151 ± 2 Ma, while the actinolitic rind yields an age of 150.9 ± 1.6 Ma. These ages are from the part of the Franciscan Complex west of the San Andreas Fault that moved northward at least 300 km with respect to the extensive Franciscan exposures east of the fault. The ages obtained in this study show that some fine-grained, low-T (lawsonite + epidote) Franciscan blueschist blocks formed at the same time as coarse-grained, high-T (garnet ± epidote) Franciscan blueschist blocks. These dated rocks indicate that both high- and low-T mafic blueschists are coeval and probably formed along 1000+ km of the North American Plate margin at ~160–155 Ma. The episode of dynamic blueschist metamorphism was soon followed by high-Mg rind formation and a long period of nearly static high-P/T conditions.

Online enhancement: appendix.

Introduction

The Franciscan Complex of California and Oregon contains blueschist-facies metamorphic rocks that form extensive coherent tracts and isolated blocks in mélange (Bailey et al. 1964; Hsu 1969; Maxwell 1974). Since the publication of the benchmark study of Ernst (1970), the Franciscan Complex has become recognized as the type example of an accretionary prism with widespread high-pressure/temperature (P/T) subduction-zone metamorphism. Many radiometric ages have been obtained from the coarse-grained, high-T (450°–550°C) garnet-epidote blueschist and very rare eclogite blocks that are widely distributed but volumetrically minor components of the Central Belt mélange terrane (e.g., Coleman and Lanphere 1971; Moore 1984; Catlos and Sorensen 2003). Many ages have also been obtained from the mostly metasedimentary terranes forming the Eastern Belt (e.g., Suppe 1969; Suppe and Armstrong 1972; Lanphere et al. 1978). Notably, the fine-grained, low-T, lawsonite-rich mafic blueschists, which are widely distributed as blocks in mélange, have rarely been dated. Most ages for this kind of block are from early work, primarily K-Ar whole-rock analyses (e.g., Lee et al. 1964; Suppe and Armstrong 1972). Except for those obtained in the studies of the Franciscan-like schists on Catalina Island, all of the ages for these blocks have been obtained from samples of Franciscan exposures east of the San Andreas Fault.

Mafic, low-T blueschist blocks vastly outnumber the coarse-grained, garnet-epidote-bearing blueschists and rare eclogitic blocks for which the Franciscan is famous. In this study, we present the first

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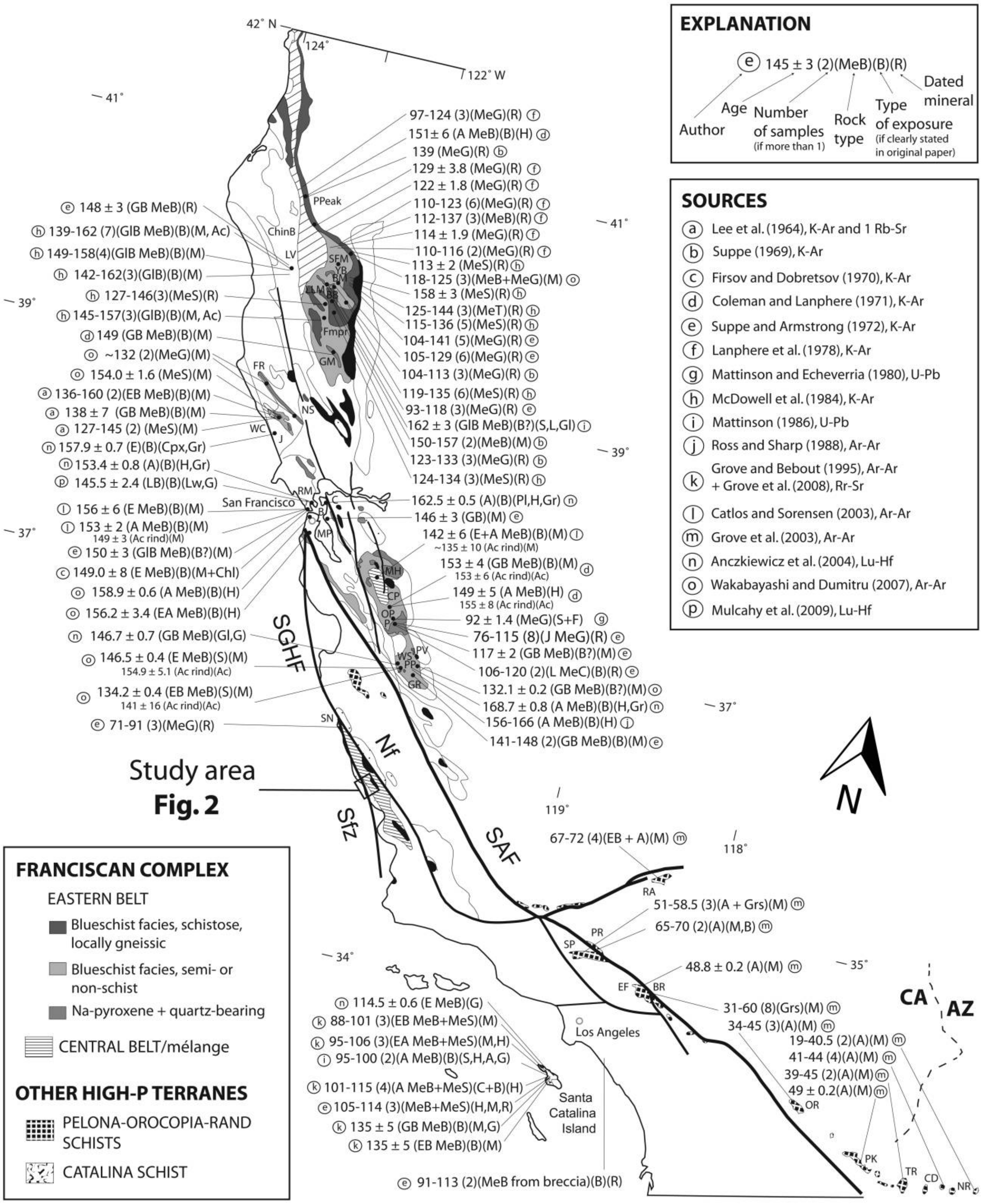

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geochronological results for mafic blueschists from the Nacimiento Block (Ernst 1980; Page 1981), located to the west of the San Andreas Fault (fig. 1). The sea cliffs and wave-cut benches near San Simeon are extraordinary in that they provide the most continuous exposure of Franciscan mélange anywhere in the Coast Ranges (Cowan 1978). This mélange is very similar to that which forms most of the Central Belt, the medial part of the Franciscan Complex north of San Francisco (Bailey et al. 1964; Cloos 1982). Reconstructions of late-Cenozoic dextral strike-slip along the San Andreas and related transform faults (Atwater 1970, 1989) place the Nacimiento Block in Southern California roughly adjacent to the Pelona-Orocopia-Rand Schist (POR) and Catalina Schist (CS) terranes, which were displaced northward from a location near the border with Mexico. Because of the lack of geochronological data from the mélange exposures in the Nacimiento Block, its relationship to the Franciscan mélange belt to the north or the POR and CS terranes to the south is debated.

The Ar-Ar ages of low-T blocks obtained in this study (fig. 2) show that the San Simeon blueschists are distinctly older than the blueschists exposed on Catalina Island (~115–90 Ma; Suppe and Armstrong 1972; Mattinson 1986; Grove and Bebout 1995; Grove et al. 2008) and the POR terrane (~75–30 Ma; Grove et al. 2003) but coeval in age with the high-T blueschist blocks in the Franciscan of Northern California (fig. 3). These new data strongly support the direct correlation of the mélange terrane in the Nacimiento Block with the Franciscan mélange terrane east of the San Andreas Fault, representing a distance of over 1000 km along the margin of North America at the time of active Franciscan subduction. Blueschists are the oldest component of this mélange terrane, and they provide additional insight into the initiation of Franciscan subduction.

Previous K-Ar and Ar-Ar Dating

The early geochronologies of Lee et al. (1964), Suppe (1969), and Suppe and Armstrong (1972), which were essential in understanding the plate-tectonic setting of California, revealed that the Franciscan high-P/low-T metamorphism was concurrent with the magmatism that created the Sierra Nevada batholith and surrounding high-T/low-P wall rocks. Lanphere et al. (1978) presented a large number of Ar-Ar ages from the phyllitic metagraywacke terrane that forms the Eastern Belt, of which most were whole-rock ages. McDowell et al. (1984) presented numerous mineral and whole-rock K-Ar ages that were obtained as part of the regional mapping transect reported by Maxwell (1974). Recently, Ar-Ar ages were reported in important studies by Catlos and Sorensen (2003) and Wakabayashi and Dumitru (2007).

This work showed that most Ar ages from the

Figure 1. Compilation of radiometric ages of high-P Franciscan rocks. Ages from Lee et al. (1964), Suppe (1969), Coleman and Lanphere (1971), and Suppe and Armstrong (1972) have been recalculated from a K-Ar decay constant of 4.72×10^{-10} to 4.963×10^{-10}, following Dalrymple (1979). Analyses with very large errors have been excluded. Location abbreviations are as follows: B, Berkeley Hills; BB, Black Butte; BM, Ball Mountain; BMS, Black Mountain Schist; BR, Blue Ridge; C, El Cerrito; CD, Castle Dome Mountains; ChinB, Chinquapin Butte; CP, Crevison Peak; EF, East Fork; Fmer, Eel River Melange; Fml, Laytonville Melange; Fmpr, Poison Rock Melange; FR+NS, Skaggs Springs Schist; GM, Goat Mountain; GR, Glaucophane Ridge; HPSZ, Hunters Point Shear Zone; J, Jenner; LLM, Leech Lake Mountain; LV, Laytonville; MH, Mount Hamilton; MP, Maclaren Park; NR, Neversweat Ridge; OP, Ortigalita Peak; OR, Orocopia Mountains; P, Pacheco Pass; PK, Peter Kane Mountains; PP, Panoche Pass; PPeak, Pickett Peak; PR, Portal Ridge; PV, Panoche Valley; RA, Rand Mountains; RM, Ring Mountain; SFM, South Fork Mountain; SN, Sur Nacimiento; SP, Sierra Pelona; T, Tiburon Peninsula; TR, Trigo Mountains; YB, Yolla Bolly; WC, Ward Creek + Cazadero; WS, Willow Springs. Dated rock types are classified as follows: A, garnet-amphibolite; GB, garnet-blueschist; GlB, glaucophane-blueschist; Grs, greenschist (only in POR and CS); LB, lawsonite-blueschist; E, eclogite; EA, epidote-amphibolite; EB, epidote-blueschist; MeB, metabasalt; MeC, metablastic; MeG, metagabro; MeS, metasediment; MeT, metatuff. All dated rocks are presumably from coherent terranes unless marked (B), indicating "block" in mélange. Dated material abbreviations are as follows: A, actinolite; B, biotite; F, feldspar; G, glaucophane; Gr, garnet; H, hornblende; L, lawsonite; M, white mica; Pl, plagioclase; R, whole rock; S, sphene. Map is after Jennings (1966), Cloos (1986), Shervais et al. (2004), Ernst et al. (2009), Wakabayashi and Dumitru (2007), and Jacobson et al. (2011). The following sources are referenced (see inset labeled "Sources"): Lee et al. (1964), Suppe (1969), Firsov and Dobretsov (1970), Coleman and Lanphere (1971), Suppe and Armstrong (1972), Lanphere et al. (1978), Mattinson and Echeverria (1980), McDowell et al. (1984), Mattinson (1986), Ross and Sharp (1988), Grove and Bebout (1995), Catlos and Sorensen (2003), Grove et al. (2003, 2008), Anczkiewicz et al. (2004), Wakabayashi and Dumitru (2007), and Mulcahy et al. (2009).

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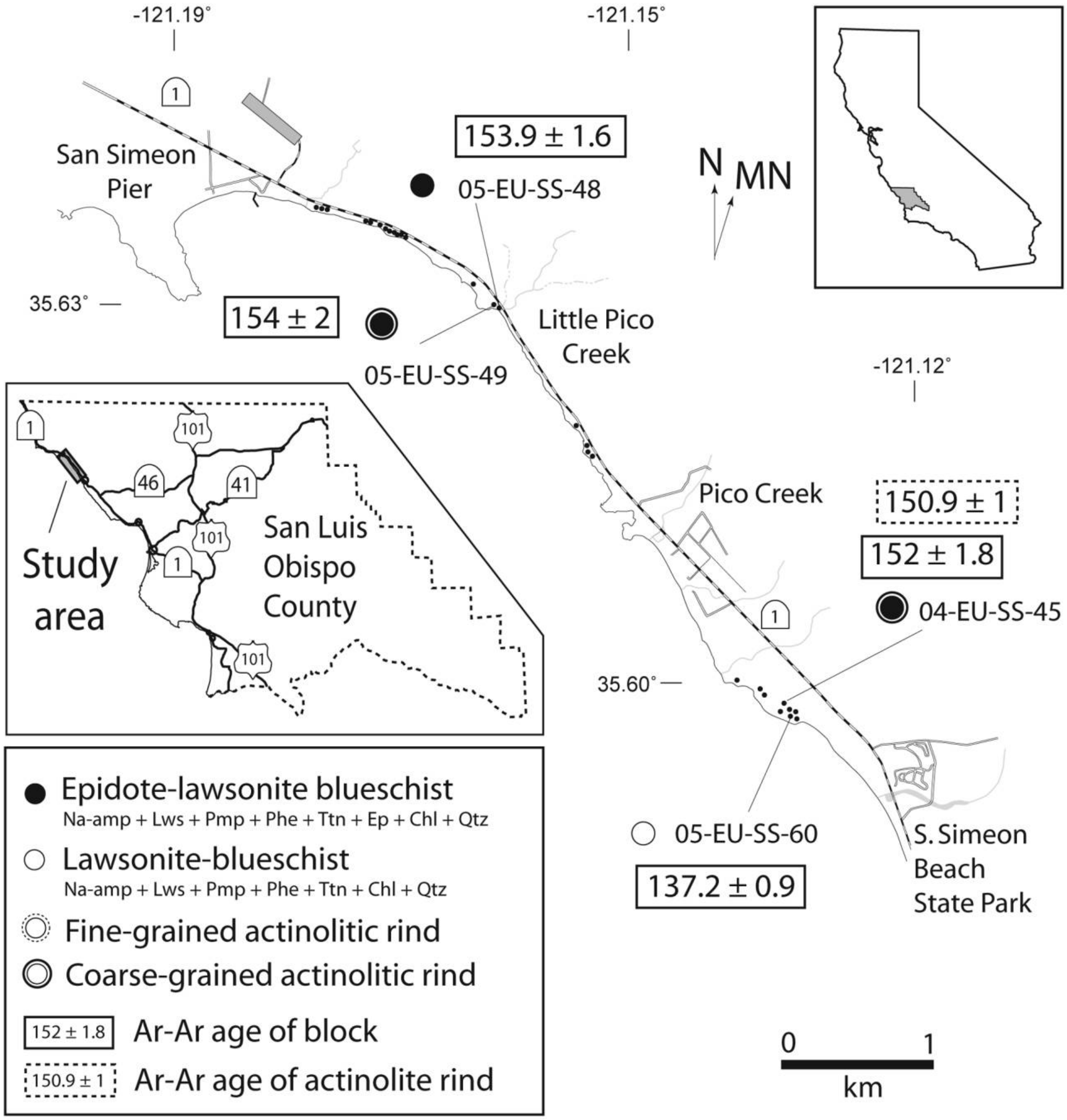

Figure 2. Map of the study area showing the locations and ages of the samples analyzed near San Simeon. Plateau ages obtained for epidote-bearing blocks are between 154 ± 2 and 152 ± 1.8 Ma. The analyzed epidote-free, lawsonite-bearing block is younger (137.2 ± 0.9 Ma). The actinolitic rind associated with epidote-bearing block 04-EU-SS-45 formed soon after the blueschist-facies metamorphism of the block (150.9 ± 1.0 Ma).

Eastern Belt are between 125 and 110 Ma, while most ages from the coarse-grained, garnet-bearing blueschists occurring as isolated blocks in the mélange belt are between 155 and 140 Ma. Debate has centered on whether the younger ages from the Eastern Belt represent the time of maximum recrystallization/peak temperature or were the result of argon loss during cooling/exhumation (e.g., Cloos 1985). Recently, Dumitru et al. (2010) combined Ar-Ar dating of metamorphism with U-Pb dating of the igneous crystallization ages of detrital zircons to convincingly show that the 100–125-Ma ages from phyllites/schists forming the Eastern Belt closely date the time of recrystallization.

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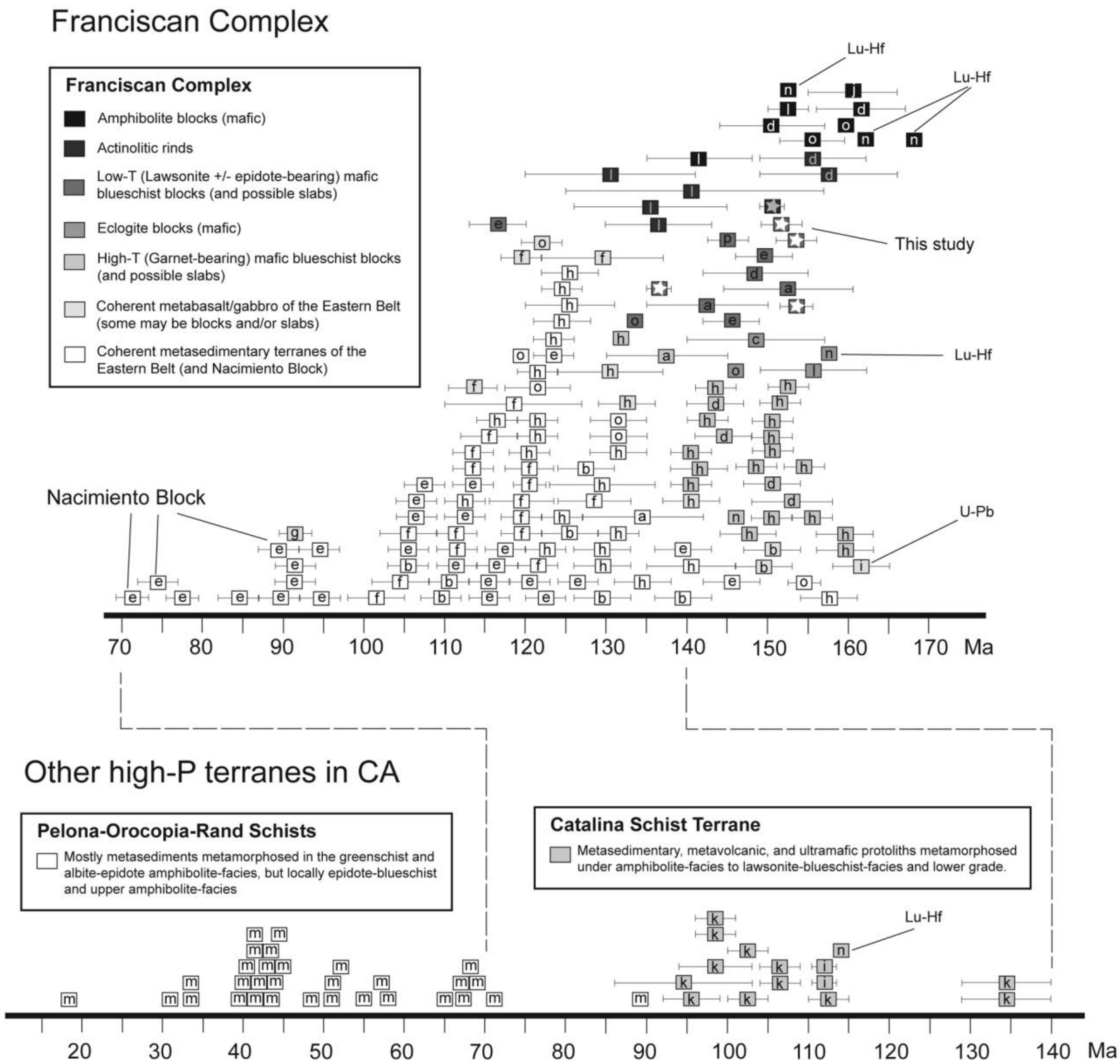

Figure 3. Histograms showing the age distribution of dated high-P rocks from the Franciscan Complex and other high-P terranes in California. References (indicated by lowercase letters) are as in figure 1. Analyses with large errors are not included. For rocks dated using more than one mineral, only the more reliable white mica ages were included.

Notably, there are very few mineral ages for fine-grained, low-T, lawsonite-rich mafic blueschists. Dozens of these kinds of blocks are clearly encased in the shale-matrix of the mélange near San Simeon. Dating these rocks is important, because they are volumetrically more important than the coarse-grained and relatively well-dated garnet ± epidote–bearing blocks. However, this dating has proven to be a challenge because the potassium content of these rocks is very low and their grain size is so fine that mineral separation is difficult. Published ages for low-T mafic blueschists range from ~150 to 120 Ma (Lee et al. 1964; Suppe and Armstrong 1972; McDowell et al. 1984; Wakabayashi and Dumitru 2007).

To help evaluate the significance of the dated samples from San Simeon, we compiled a map of the published ages for the Franciscan Complex (fig. 1). Because of the scarcity of contact exposures, controversy exists in some areas regarding the nature and lateral continuity of some blueschist exposures. Nearly all authors agree that the Eastern Belt north of San Francisco (Bailey et al. 1964), which contains widespread lawsonite and arago-

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nite, is mostly a low-T metasedimentary terrane that is relatively coherent, because depositional layering maintains a similar character and orientation at scales of hundreds of meters to kilometers. Jadeitic pyroxene + quartz–bearing metamorphics form a similar coherent terrane in the core of the Diablo Range, a tectonic window through the Great Valley forearc basin (Ernst et al. 1970). In contrast, much of the Central Belt is a mélange terrane similar to that which is exposed in the sea cliffs near San Simeon, with blocks of blueschist dispersed in a weakly metamorphosed, pumpellyite ± lawsonite–bearing shale-matrix (Cloos 1983).

Many high-T blueschists, such as the one near Ring Mountain on the Tiburon Peninsula and those in other parts of the Central Belt, are roughly elliptical in shape and up to several tens of meters in diameter. These high-T blocks are noted for having masses of actinolite/tremolite ("rinds") along their margins that are remnants of reaction zones between metabasalts and serpentinized ultramafic rocks (Coleman and Lanphere 1971; Moore 1984). However, contact relations in the Franciscan are rarely exposed, and the lateral extents of some bodies of blueschist are so unclear that classification of some areas as either coherent or mélange can be debated. Several exposures are hundreds of meters long, which has led some authors to propose that several mafic units are elongate slabs (e.g., Ward Creek: Coleman and Lee 1963; Panoche Pass: Wakabayashi and Dumitru 2007).

In order to minimize some of the confusion in the literature, the Franciscan blueschists in figure 1 are classified as (1) coherent, with mostly metasediments and with lesser volcanics, mostly from the Eastern Belt, or (2) blocks in mélange that are either (a) coarse, high-T (garnet-bearing) or (b) fine, low-T, mostly isolated mafic blocks from the Central Belt.

Figure 1 shows that the Franciscan of the Nacimiento Block lacks geochronological study. The nearest ages for Franciscan metamorphics are from the Diablo Range to the northeast and the Franciscan-like CS and POR to the south (figs. 1, 3). Tectonic restorations of dextral slip along the San Andreas and related faults place the Nacimiento Block at latitudes between Los Angeles and the California border with Mexico (Atwater 1970, 1989), and the CS would be restored to a location even farther south, along strike-slip splays that trend offshore. The Ar-Ar phengite mineral ages presented in this article are the first from the Nacimiento Block, the first from the area of exceptional mélange exposure near San Simeon, and among the first for low-T, fine-grained, lawsonite-rich Franciscan blueschists.

Samples

This article is an outgrowth of an investigation designed to fully characterize the blueschists that occur in a 6-km stretch of shale-matrix mélange near San Simeon (Ukar 2010). Petrographic analysis of 34 blueschist blocks has confirmed that this tract of mélange lacks coarse, high-T garnet-epidote blueschists but contains dozens of fine-grained, low-T lawsonite ± epidote mafic blueschists. These blueschist blocks are clearly encased in the shale-matrix of the mélange (Hsu 1969), with pinching and swelling showing all gradations into boudinage that was accommodated by cataclastic flow (Cowan 1978; Ukar 2012). Similar to the low-T, lawsonite-bearing blueschists that occur as blocks in the rest of the Franciscan, these blocks are also nearly entirely of mafic composition. Micas or other K-rich minerals are scarce, because these rocks have low potassium contents.

Although the mineralogy of high-T blueschist blocks is recognizable in hand samples and easily confirmed with an optical microscope, detailed petrographic characterization of low-T blocks is limited because their grain sizes are typically smaller than a few hundred microns. High-magnification techniques such as backscattered electron imaging (BSE) also reveal complex mineral intergrowths and compositional zonation (E. Ukar and M. Cloos, unpublished data), which make whole-rock Ar ages difficult to reproduce.

Dating of low-T mafic blueschists has been limited because of their low potassium contents and fine grain sizes, which hinder mineral separation. During a petrographic characterization of nearly 250 samples from San Simeon, four low-T blueschist blocks were found that contained layers that were relatively rich in coarse phengitic mica and thus suitable for mineral separation and Ar dating. Electron microprobe analyses identified the mica in these samples as phengite (3.2–3.9 Si atoms per formula unit), which is conformable with the surrounding Na-amphibole and lawsonite and defines a strong penetrative foliation created during dynamic recrystallization.

All four of these phengite-rich blocks also contain Na-amphibole, lawsonite, chlorite, pumpellyite, titanite, and quartz (fig. 2). Blocks 04-EU-SS-45 (we also dated the associated "actinolitic rind"; see below), 05-EU-SS-48, and 05-EU-SS-49 also contain epidote. Block 05-EU-SS-60 (which yielded the

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youngest age) is epidote free, but it shows compositional zoning in the sodic amphiboles, which indicates a probable early metamorphic event under epidote-lawsonite blueschist conditions. Estimated peak temperature conditions attained by epidote-bearing blocks are 300°–350°C at minimum pressures of 5 kbar, and for lawsonite-bearing, epidote-free blocks they are 200°–250°C at similar pressures (Ukar 2010; E. Ukar and M. Cloos, unpublished data).

During field work, nine blocks were discovered with patches of actinolite/tremolite along their edges that are mineralogically very similar to the rinds present on high-T Franciscan blueschists and rare eclogites (E. Ukar and M. Cloos, unpublished manuscript). The rind associated with block 04-EU-SS-45 is composed of Mg-rich actinolite, and enough coarse phengitic white mica was present that a mineral separation could be obtained.

^{40}Ar-^{39}Ar Ages of Blueschist Blocks in San Simeon

The phengitic micas from the San Simeon blueschists were separated from crushed samples and carefully hand-picked for purity. They were dated via ^{40}Ar-^{39}Ar laser incremental heating analysis. The appendix, available in the online edition or from the *Journal of Geology* office, describes the materials and methods used. Step-heating plateau ages, as defined by Fleck et al. (1977), of the analyzed samples are shown in figure 4 (see also table A1, available in the online edition or from the *Journal of Geology* office). A complete set of the tabulated data for each incremental heating step is provided in table A2, available in the online edition or from the *Journal of Geology* office. Plateau-age errors are reported at the 95% confidence level (2σ) and include the errors in the irradiation correction factors and the error in the J-factor but not the uncertainty in the potassium-decay constants. Each sample was analyzed twice, and the results from both runs are shown in each graph in figure 4. Plateau ages were calculated as the mean weighted by inverse variance, and plateau-age errors were calculated as the standard error of the weighted mean. If the MSWD was greater than 1, then the errors were calculated as the standard error of the weighted mean multiplied by the square root of the MSWD. Integrated ages were calculated by isotopic recombination of steps, and integrated age errors were calculated as the standard error of the weighted mean (see Vasconcelos et al. 2002).

Integrated ages obtained for the epidote-bearing blocks 04-EU-SS-45, 05-EU-SS-48, and 05-EU-SS-49 are 152.0 ± 1.8, 153.9 ± 1.6, and 154 ± 2 Ma, respectively (figs. 2, 4). The age of the micaceous actinolitic rind associated with block 04-EU-SS-45 is 150.9 ± 1.6 Ma, which is coeval with the mica from the mafic part of the block. Block 05-EU-SS-60, which lacks epidote, yielded a significantly younger age of 137.2 ± 0.9 Ma.

These white mica separates are very fine grained, ~125–150 μm in size. The host rocks attained peak temperatures of about 350°C (E. Ukar and M. Cloos, unpublished data). However, the closure temperature for Ar loss from fine-grained phengite is not well known. The closure temperature of Ar in coarse muscovite is commonly assumed to be ~350°C (McDougall and Harrison 1988), but a recent study suggests that in some white mica it might be higher, ~415 °C (Harrison et el. 2009). The ^{40}Ar-^{39}Ar ages obtained in this study are interpreted as dating the age of dynamic recrystallization. This interpretation is most strongly supported by the flat plateaus obtained for Ar release, but this behavior could also result from very rapid cooling. If the Ar closure temperature in these fine-grained phengites was lower than ~300°C, then these white mica ages would record a cooling age. However, if this occurred, the age spectra would probably exhibit age profiles that would not be flat, because of varied Ar loss by diffusion (Harrison et al. 2009).

Another issue of concern is excess ^{40}Ar. Excess Ar has been observed in many high-pressure and ultrahigh-pressure (UHP) terranes around the world (e.g., Sherlock and Kelley 2002). This can significantly disturb the system, making the Ar ages older than the ages of recrystallization or cooling. A regression to the ^{40}Ar-^{36}Ar intercept in an inverse isochron plot (fig. A1, available in the online edition or from the *Journal of Geology* office) is commonly used to assess the presence of excess Ar in samples. In the San Simeon samples, all of the heating steps are highly radiogenic, and all steps plot close together on inverse isochron plots, away from the atmospheric intercept. This behavior limits the use of such plots to draw conclusions about the presence or absence of excess Ar. The reliability of Ar ages is based on (1) the geometry of age spectra and (2) the consistency of data between samples. The San Simeon age spectra do not show a curvature that would result from the presence of even minor amounts of excess Ar or a mixing of Ar from two generations of micas (e.g., Dumitru et al. 2010). Moreover, the ages obtained for petrologically similar San Simeon samples are statistically indistinguishable. On the basis of the consistency of the

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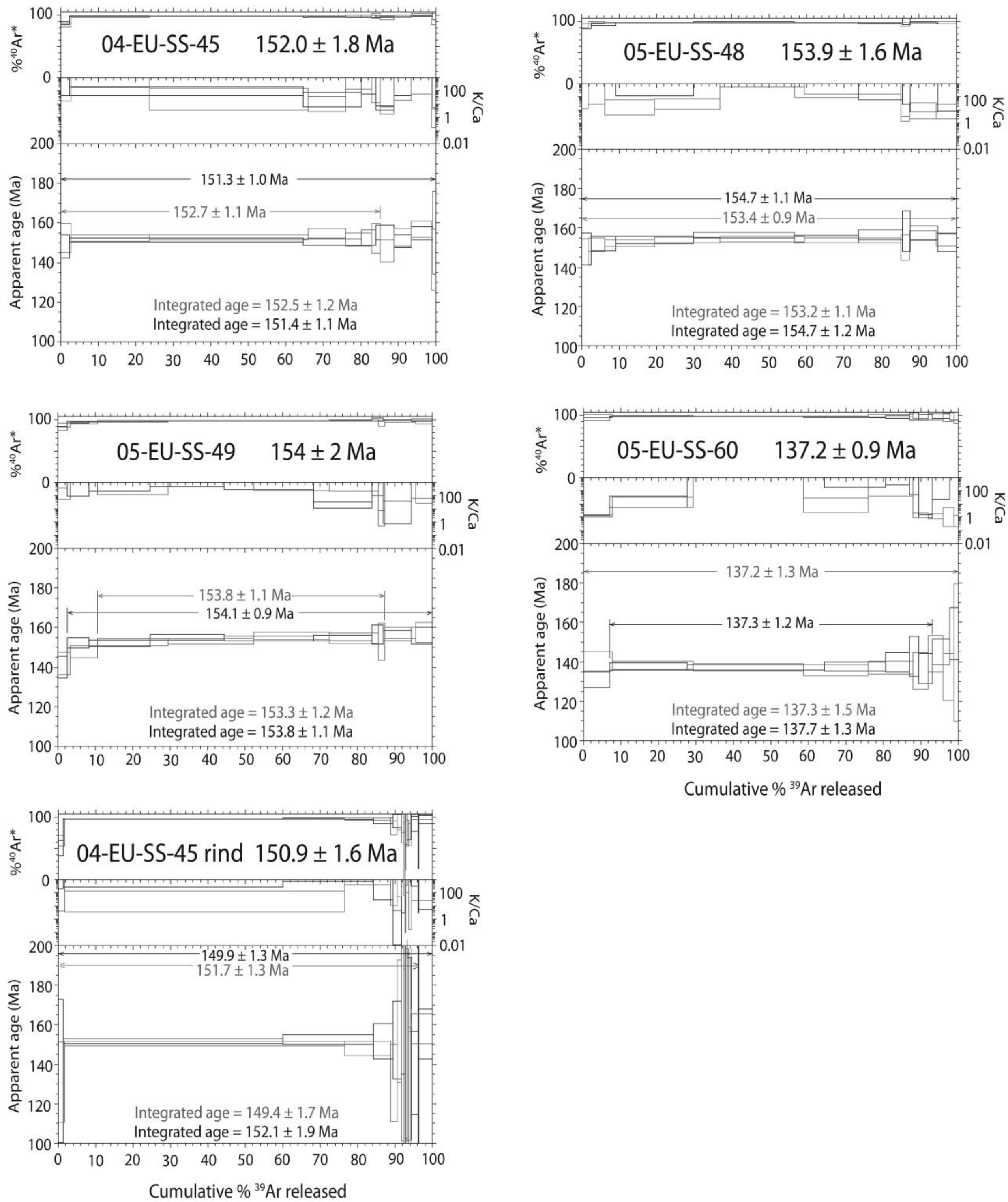

Figure 4. ^{40}Ar-^{39}Ar step-heating spectra of analyzed phengite samples from near San Simeon. Each sample was analyzed twice (black and gray spectra in each graph). Epidote-bearing blocks are 156–149 Ma. The one epidote-free, lawsonite-bearing block we analyzed is younger. The age of the actinolitic rind associated with blueschist block 04-EU-SS-45 confirms that this rind formed soon after the block was metamorphosed under lawsonite + epidote blueschist conditions.

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data, and because of similarity with other ^{40}Ar-^{39}Ar ages reported for other localities in the Franciscan (fig. 3), we do not believe that excess argon has affected the age determination.

Discussion: Evolution of P-T Conditions during Franciscan Subduction

The ages presented in this article confirm the correlation of the rocks exposed at San Simeon with those from Franciscan localities to the north. ^{40}Ar-^{39}Ar ages of low-T mafic blueschists from the rest of the Franciscan vary from 155 to about 120 Ma (Coleman and Lanphere 1971; Suppe and Armstrong 1972; Wakabayashi and Dumitru 2007; figs. 1, 3). Therefore, these new ^{40}Ar-^{39}Ar ages are among the oldest for low-T mafic blueschists. These ages confirm that low-T (300°–350°C) lawsonite-epidote blueschists formed at the same time as high-T (450°–550°C) garnet-epidote blueschists (fig. 5; also see Ukar 2012).

The Franciscan of Central and Northern California is emplaced beneath the Coast Range Ophiolite (CRO), which contains plagiogranites that yield zircons at many locations that date between ~170 and 161 Ma (Hopson et al. 1981, 2008; Shervais et al. 2005). The 150–155-Ma ages for Franciscan blueschists indicate that subduction must have begun along the western margin of the North American Plate soon after formation of the CRO, between about 160 and 155 Ma. A probable zone of weakness along which plate convergence could have initiated is the boundary between the old, cold Farallon Plate and the newly formed, hot, buoyant, and thin lithosphere capped by the CRO (see Ukar 2012). On the basis of Cenozoic tectonic-plate reconstructions, similar blueschist-facies conditions must have developed soon after the initiation of subduction along the California margin over a distance of more than 1000 km. We recognize that Dickinson (1983) and Jacobson et al. (2011) proposed a reconstruction that invokes hundreds of kilometers of sinistral strike-slip along the Nacimiento Fault during Cretaceous subduction. If this were the case, the San Simeon area would probably have been closer to its present location in Central California. Nonetheless, the length of the early Franciscan subduction zone must have been at least 1000 km.

It is necessary to point out that there are a few ages from high-T amphibolite blocks in the Franciscan that are older than ~160 Ma. Ross and Sharp (1986, 1988) obtained four Ar-Ar ages for a single garnet-amphibolite block that cluster at 161 ± 5 Ma, whereas Anczkiewicz et al. (2004) obtained two Lu-Hf ages of 168.7 ± 0.8 and 162.5 ± 0.5 Ma for two similar blocks (figs. 1, 3). These ages indicate that garnet-amphibolite conditions predated blueschist-facies conditions. Two explanations can be proposed for the garnet amphibolites with ages concurrent with CRO formation: (1) they might have formed during tectonism and metamorphism along transform faults connecting the segments of the spreading ridge forming the CRO, or (2) they might have formed at shallow depths as the result of imbricate faulting of hot oceanic crust during slow convergence before the initiation of Franciscan subduction.

Because the CRO is young and forms the hanging wall, only a small amount of sediment would have been present along the margin when subduction started (fig. 5*c*). The small sediment cover probably facilitated the underplating of pieces from the top of the subducting oceanic crust along the bottom of the overriding plate. Once accreted by underplating, rapid underthrusting of the Farallon Plate would have caused cooling. On the basis of geothermometrical and geochronological data, Anczkiewicz et al. (2004) argued for a slow initial cooling, and therefore slow subduction, assuming that amphibolite-facies rocks formed in the subduction zone. We favor a model in which subduction started relatively quickly, ~5 cm/yr as concluded by Page and Engebretson (1984), which was soon followed by a period of slow, highly oblique convergence starting at ~145 Ma. Early subducted materials were heated by the young and hot hanging wall that cooled rapidly to temperature/depth gradients approaching ~15°C/km by ~145 Ma (fig. 6*a*). Early formed and accreted blueschists and eclogites would experience a counterclockwise P-T path (Cloos 1982), which has been observed in many blocks from the Franciscan mélange (e.g., Cloos 1986; Wakabayashi 1990; Krogh et al. 1994; Tsujimori et al. 2006), including the San Simeon blueschists (E. Ukar and M. Cloos, unpublished data).

The nearly coeval metamorphic ages of the actinolite rind and host low-T blueschist block (04-EU-SS-45) obtained in this study are in agreement with results obtained for actinolitic rinds associated with other Franciscan high-T blueschist and eclogite blocks (e.g., Catlos and Sorensen 2003; figs. 1, 3). This indicates that the metasomatic reaction that formed the Mg-rich rinds occurred soon after dynamic high-P metamorphism ended. Fragments of mafic ocean crust ± seamount fragments were dynamically metamorphosed and intersliced with mantle material along the base of the overriding plate during the early stages of subduction. Continued convergence caused cooling, and the upward infiltration of subducted water altered the ultra-

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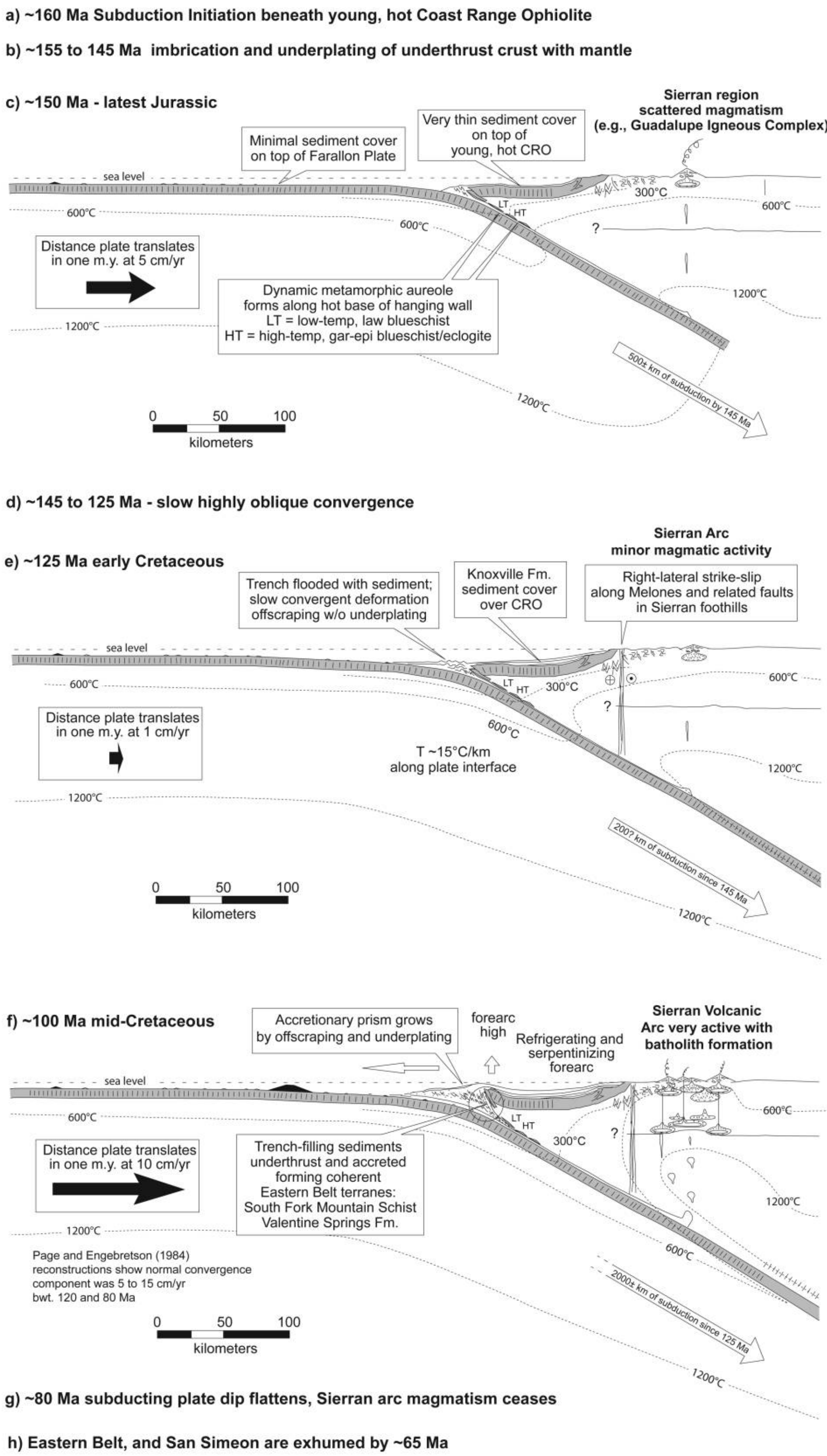

Figure 5. Tectonic evolution of the western North American Plate margin between 160 and 80 Ma. See text for explanation. Also see Ukar (2012).

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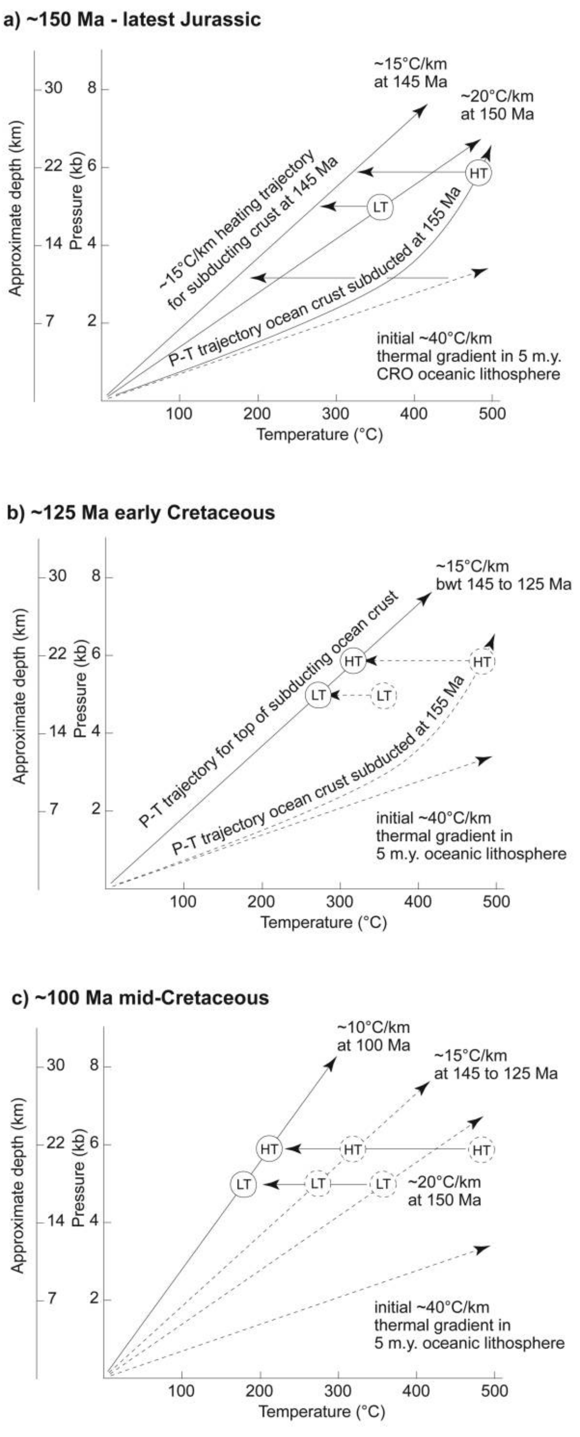

Figure 6. P-T trajectory during Franciscan subduction. HT, high temperature; LT, low temperature.

mafic rock to serpentine. As the mantle rocks hydrated, actinolitic rinds formed along block/serpentine contacts under relatively static conditions (Ukar 2012; E. Ukar and M. Cloos, unpublished manuscript).

Direct evidence for a period of very slow subduction between ~145 and 125 Ma comes from the scarcity of magmatism in the Sierra Nevada batholithic belt during this timespan (e.g., Chen and Moore 1982; Armstrong and Ward 1993). During this time, the trench was flooded with sediment that would later subduct to become part of the Eastern Belt and Diablo Range coherent terranes (fig. 5*e*). U-Pb analyses of detrital zircons indicate that most of the sediments that form these coherent metasedimentary terranes were accreted between ~125 and 110 Ma (Dumitru et al. 2010). At ~125 Ma, subduction speed accelerated and the extensive blanket of sediments was imbricated and underplated at blueschist-facies depths (fig. 5*f*). The 137-Ma age of the lawsonite-rich, epidote-free block 05-EU-SS-60 indicates that deep in the subduction zone, low-T dynamic blueschist-facies conditions were sustained until at least ~135 Ma. The ages of the blueschist-facies rocks forming the South Fork Mountain Schist indicate that the temperature/depth gradients were ~15°C/km at ~120 Ma (fig. 6*b*). Fast, continuous subduction of cold oceanic lithosphere caused more refrigeration of the forearc hanging wall block (Cloos 1985; Dumitru 1991). At a given depth, material could then be underplated at progressively lower temperatures. Temperature/depth gradients became less than ~10°C/km by about 100 Ma (fig. 6*c*), as evidenced from the presence of jadeitic pyroxene + quartz in sediments that were once buried to 20–30 km in the Pacheco Pass area (Ernst et al. 1970, 2009; Ernst 1993; Tripathy et al. 2005; Tripathy 2006).

The formation of the CS terrane at 115–90 Ma (Mattinson 1986; Grove and Bebout 1995; Grove et al. 2008) corresponds to the onset of fast subduction along Central and Northern California. This terrane formed south of the main body of the Franciscan and experienced a metamorphic history that was significantly different, probably because of the proximity of underthrusting to the plutonic roots of the volcanic arc (Grove et al. 2008).

Mafic blueschist blocks in the Franciscan mélange are pieces of the early-formed metamorphic aureole at the base of the North American Plate that became detached and transported to shallow depths in upwelling shale-matrix mélange (Cloos 1982, 1984). Ukar (2012) proposed a model in which extensional exhumation of Franciscan Eastern Belt coherent terranes, as well as the upwelling of subducted sediment to create shale-matrix mélange, were facilitated, if not triggered, by the shallowing of the plate dip beginning around 80 Ma that caused the Laramide Orogeny (Coney and Reynolds 1977). This episode of flat-slab subduction probably also

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facilitated the creation of the POR schists between 70 and 30 Ma farther inland and directly beneath the plutonic roots of the arc (Jacobson et al. 2011).

Conclusions

This article presents the first ^{40}Ar-^{39}Ar ages for mafic low-T blueschist blocks encased in the extraordinary shale-matrix mélange exposures near San Simeon, California. The 154–151-Ma ages for these blueschists show that the Franciscan rocks forming the Nacimiento Block correlate with the Central Belt of Northern California and the Diablo Range window.

The highest-T, high-P metamorphism occurred between ~155 and 150 Ma and was quickly followed by actinolite rind formation. These results and regional relationships indicate that dynamic metamorphism of subducted ocean crust and interslicing with mantle material at the base of the North American Plate probably occurred concurrently along 1000+ km of the length of the California margin.

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